Nyquist-Shaped Dispersion-Precompensated Subcarrier Modulation with Direct Detection

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Abstract: We report on the first experimental demonstration of 14 Gb/s direct detection single-sideband subcarrier modulated Nyquist QPSK transmission. Using electronic pre-compensation, transmission over 800 km of dispersion-uncompensated standard single-mode fiber was achieved.

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1. Introduction

The increasing demand to achieve both higher bit rates and spectral efficiency using cost-effective systems is especially strong in metro and access optical communication. For long-haul applications, multilevel phase and amplitude modulation techniques combined with coherent detection allow high spectral efficiency and the ability to mitigate transmission impairments. However, for metro, access and backhaul applications, coherent detection schemes may not be cost-effective. For this reason, subcarrier modulated (SCM) QPSK or QAM signaling using RF-subcarriers to encode the data is an attractive approach for multilevel signaling in direct direction systems, avoiding the need for costly components such as optical hybrids, local oscillators and balanced detectors. The number of subcarriers can vary from one to many, an example of the latter being optical frequency division multiplexing (OFDM) [1]. A shortcoming of the multi-subcarrier modulation is the high peak to average power ratio (PAPR), which leads to a degradation in receiver sensitivity [1]. Alternatively, a single RF-subcarrier can be used to reduce PAPR. For high spectral efficiency, the subcarrier frequency spacing from the optical carrier should be as low as possible, which can be achieved by minimizing the sideband spectral width using a pulse-shaping filter. The lowest possible subcarrier frequency can be equal to half of the baud rate, called half-cycle Nyquist-SCM (N-SCM) [2]. However, half-cycle N-SCM has the highest PAPR compared to other N-SCM with different roll-off factors or non pulse-shaped SCM such as single-cycle [3]. Hence, it causes a significant penalty in receiver sensitivity as presented in [4]. In this work, we therefore consider Nyquist SCM with a roll-off factor of 0.3 which offers a good trade-off between the receiver sensitivity and spectral efficiency.

In direct detection systems, the phase of the optical field is lost upon photodetection. However, chromatic dispersion (CD) can be compensated at the transmitter, without the need of any optical dispersion compensation (ODC) unit, by applying electronic pre-dispersion (EPD) [5, 6].

To the best of our knowledge, this is the first time direct detection single-sideband subcarrier modulated Nyquist QPSK is experimentally assessed in transmission over uncompensated standard single-mode fiber (SMF) by applying EPD. Transmission without ODC unit at a bit rate of 14 Gb/s was successfully demonstrated over 400 and 800 km.

2. Experimental Setup

The experimental setup used for transmission is shown in Fig. 1. Data was modulated by using an IQ-modulator. It was then transmitted over standard SMF fiber and detected by a single-ended photodiode followed by a TIA and subsequently captured by a single ADC. The IQ-modulators were driven by two FPGA-DAC (Micram VEGA DACII) pairs, with a nominal resolution of 6-bits and a sampling rate of 28 GSa/s. The generation of two driving signals as shown in Fig. 2(a) was carried out offline in MATLAB before the waveforms were uploaded to FPGA-RAM memory.

First, 2^{15} de Bruijn bit sequences were used to generate a conventional 14 Gb/s QPSK signal. A pair of root-raised cosine (RRC) pulse-shaping filters with a roll-off factor, α, of 0.3 and upconversion to a subcarrier frequency, f_{sc}, of 5.25 GHz (0.75 of the symbol rate) were applied to the in-phase (I) and quadrature (Q) components, separately. The I-

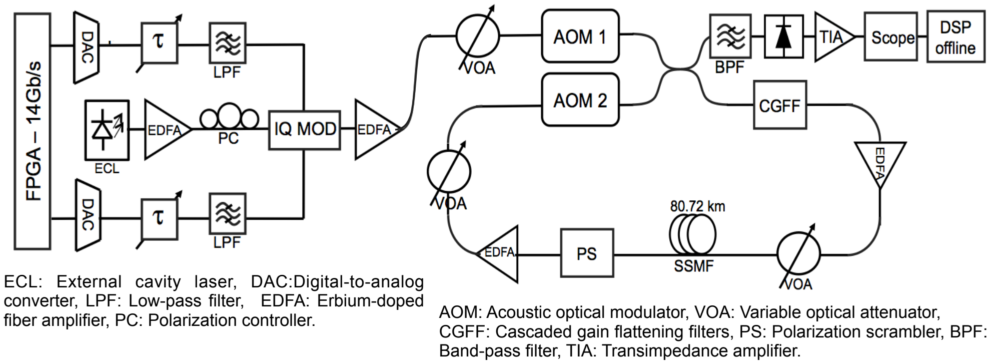

Fig. 1: Experimental Setup.

and Q-components were then added and the lower sideband was removed with a digital filter. In order to mitigate the dispersion accumulated along the fiber, EPD was applied to the signal (the inverse of the channel response due to CD) as described in [5, 6].

An ECL with a linewidth of 100 kHz at 1550 nm was used as a laser source, amplified and then modulated. The IQ-modulator was operated at the quadrature point to map the electrical domain to the optical domain linearly. Before the recirculating loop, the optical signal was re-amplified to compensate for losses at the transmitter.

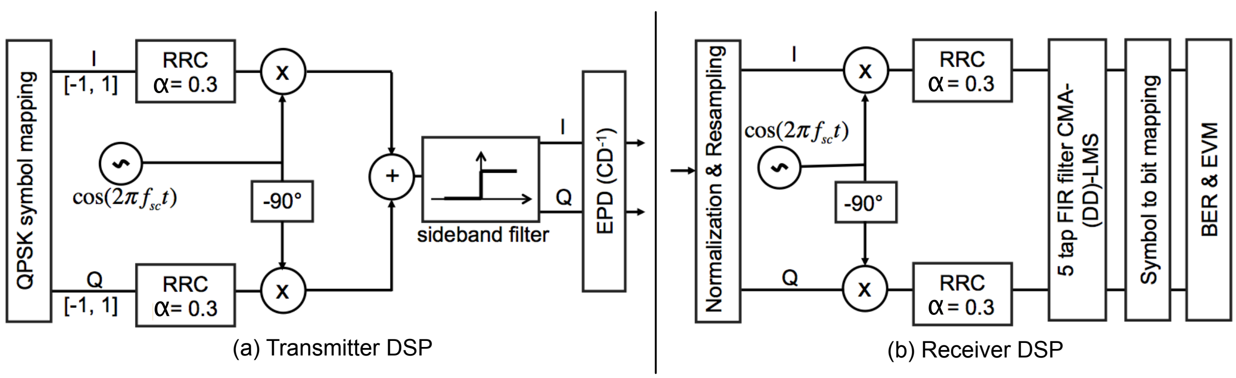

Fig. 2: (a) Transmitter and (b) receiver designs.

The dispersion tolerance of the proposed modulation format was investigated by transmitting the signal over 400 km and 800 km. A recirculating fiber loop with a single 80.72 km span of standard SMF fibre (15.4 dB loss) was used to perform the transmission without any ODC unit. An optical filter was used to suppress out-of-band amplified spontaneous (ASE) noise and for gain-flattening. EDFAs with a noise figure of 4.5 dB were operated at saturation point (18 dBm). A variable optical attenuator (VOA) was used to control the launch power into the fibre span. Optimum launch power was determined by varying the power and monitoring the error vector magnitude (EVM) [7]. A 2^{nd}-order super-Gaussian type band-pass filter (BPF) with a bandwidth (BW) of 0.55 nm was employed to remove the out-of band noise before signal detection at the receiver. Following detection by the single-ended PIN photodiode, a single ADC (Tektronix DPO 72004 scope) with a sampling rate of 50 GSa/s and a electrical BW of 16 GHz digitized the signal. After acquiring the transmitted signal, resampling to 2 Sa/s, normalization, conversion to baseband signal and a matched filter were applied as illustrated in Fig. 2(b). For the clock recovery, initally, a 5-tap CMA-LMS equalizer was used before switching to decision directed mode. Finally, the error vector magnitude (EVM) was measured and the bit error rate (BER) was computed by error counting.

3. Results

The received digital spectrum and constellation diagram after 800 km (10 spans) are shown in Fig. 3(a) and (b). The frequency roll-off and Nyquist pulse shaping cause a distortion that can be observed in Fig. 3(b). The back-to-back (B2B) noise-free signal has an EVM of 12%. The optimum carrier to signal power ratio (CSPR) varies with the OSNR level. It increases with higher OSNR because the system is ASE noise-limited whereas at low CSPR, distortions due to subcarrier to subcarrier intermixing cause a degradation in the receiver sensitivity. In this experiment, CSPR was set to 3 dB in order to operate at the quadrature point of the IQ-modulator.

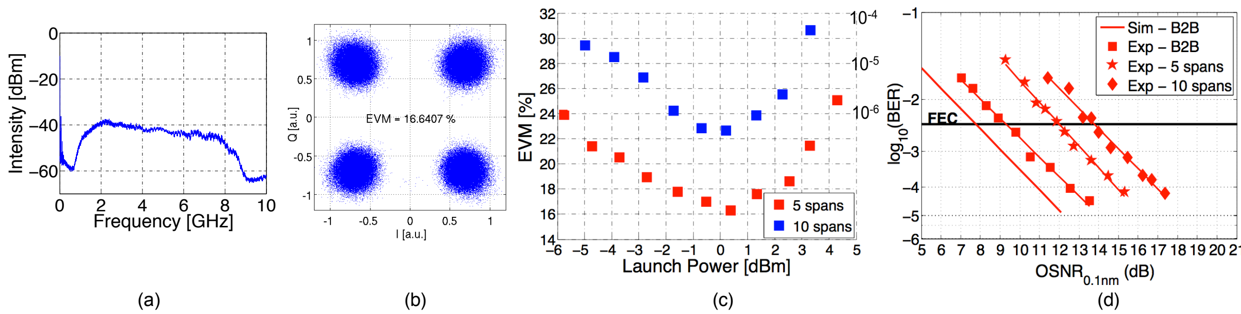

Fig. 3: (a) Received digital spectrum, (b) Constellation after 10 spans, (c) EVM vs launch power in the presence of ASE noise, (d) BER vs OSNR.

To achieve the transmission with the lowest possible BER, the launch power was swept from -6 dBm to 5 dBm and EVM was measured for both 5 and 10 spans, as plotted in Fig. 3(c). The optimum launch power was found to be approximately 0 dBm for both distances. At the optimum launch power, EVMs of 14% and 17% were achieved at 5 and 10 spans, respectively.

Next, ASE noise was added at the receiver to quantify the required OSNR at the optimum launch power. The required OSNR levels for 400 and 800 km were found to be 12.0 dB and 13.8 dB at the FEC limit of 3.8×10^{-3} (see Fig. 3(d)). In OSNR measurements for 400 and 800 km, penalties of 2.8 dB and 4.6 dB were observed compared to the B2B case, respectively. The penalty is due to the quantization noise incurred because of the EPD at the transmitter. Additionally, the non-ideal CSPR ratio to operate at the linear regime of the modulator and nonlinearities of the fiber, particularly for 800 km.

4. Conclusions

Single-sideband subcarrier modulated Nyquist-QPSK (SSB SCM N-QPSK) at a bit rate of 14 Gb/s was experimentally assessed in a direct detection link. Electronic pre-dispersion allows the compensation of chromatic dispersion successfully to achieve a transmission over uncompensated links over 400 and 800 km. To our knowledge, this is the first transmission demonstration of dispersion pre-compensated SSB SCM N-QPSK.

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References

1. A.J. Lowery and L.B. Du, *Optical Fiber Tech.*, **17**, 421–438 (2011).
2. A. Karar and J. Cartledge, *IEEE Photonics Tech. Letters*, **25**, 757–760 (2013).
3. A.O.J. Wiberg *et al.*, *OFC 2009*, paper OTuE1.
4. M.S. Erkilinc *et al.*, *ECOC 2013*, paper Th3C4.
5. R.I. Killey *et. al.*, *IEEE Photonics Tech. Letters*, **17**, 714–716 (2005).
6. J. McNicol *et. al.*, *OFC 2005*, paper OThJ3.
7. R. A. Shafik, S. Rahman, R. Islam, and N. S. Ashraf, 2^{nd} *Int'l. Conference on Emerging Technologies,* (2006).